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SAPPHiRE: a Small $\gamma\gamma$ Higgs Factory

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Abstract

A new particle with mass ~ 125 GeV that resembles the Higgs boson has recently been discovered by ATLAS and CMS. We propose a low-energy $\gamma\gamma$ collider as a cost- and time-efficient option for a Higgs factory capable of studying this particle in detail. In the past, this option has been suggested as a possible application of the CLIC two-beam accelerator technology (the CLIC Higgs Experiment, CLICHE) or as an option for the ILC. Here we propose a design based on a pair of ~ 10 GeV recirculating Linacs (Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons, SAPPHiRE) similar in design to those proposed for the LHeC. We present parameters for the e^- beams and sketch a laser backscattering system capable of producing a $\gamma\gamma$ peak luminosity of $0.36 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ with $E_{CM}(\gamma\gamma) \sim 125$ GeV. A $\gamma\gamma$ collider with such a luminosity could be used to measure accurately the mass, $\bar{b}b$, WW^* , and $\gamma\gamma$ decays of the Higgs boson. We also comment on possible synergies with other projects such as LHeC, the ILC or CLIC, and on other physics prospects in $\gamma\gamma$ and $e^-\gamma$ collisions.

1 Introduction

The discovery by ATLAS and CMS [1] of a new boson h with mass ~ 125 to 126 GeV that decays into photon pairs and Z pairs naturally focuses attention on possible future accelerator facilities that would offer timely and cost-effective opportunities for future detailed studies of its properties. The LHC has already made rapid strides towards the identification of the h particle, demonstrating that it cannot have unit spin and that its couplings to other particles are approximately proportional to their masses, as would be expected for a Higgs boson. The LHC will make much more progress in the coming years, determining its spin and measuring its couplings much more accurately, with the possibility of measuring its trilinear self-coupling with the high-luminosity upgrade of the LHC.

However, proton-proton collisions are not ideal for studying the properties of a Higgs boson, and now is the time to discuss in the most open-minded way options for supplementing the studies possible with the LHC. For example, electron-positron and muon-antimuon collisions offer much cleaner experimental collisions, and so are attracting growing attention. Here we advocate another option for detailed studies of the h boson, namely $\gamma\gamma$ collisions. These are often regarded as adjuncts to linear e^+e^- colliders such as the ILC or CLIC [2]. However, some years ago we proposed as an alternative equipping the low-energy CLIC demonstrator project CLIC-1, which is designed to collide two low-emittance e^- beams with energies ~ 70 GeV, with a laser backscattering system capable of producing high-luminosity $\gamma\gamma$ collisions with $E_{CM}(\gamma\gamma) \sim 120$ GeV (the CLIC Higgs Experiment, CLICHE) [3].

Here we propose an alternative concept based on a pair of ~ 10 GeV recirculating Linacs similar in design to those proposed for the LHeC [4] (Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons, SAPPHiRE). Equipped with with a laser backscattering system similar to that proposed for CLICHE, this facility should be capable of a $\gamma\gamma$ peak luminosity of $0.36 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, sufficient to produce tens of thousands of h particles per year in very clean experimental conditions. Obvious advantages of a $\gamma\gamma$ -based Higgs factory include (1) the lower beam energy required to produce the Higgs boson in the s channel, namely about 80 GeV, as compared with 120 GeV required in e^+e^- collisions - allowing for efficient recirculation and for an RF installation that is about 10 times smaller and hence a significant saving, (2) the possibility of high polarization in both the primary e^- and the colliding γ beams - in contrast to the case of e^+ , and (3) the absence of the need to produce positrons - another potential large saving and simplification.

In subsequent sections of this paper, we first recall some aspects of the accelerator requirements for $\gamma\gamma$ Higgs factories, including the e^- beam parameters and the laser backscattering system, that would be needed to attain a luminosity sufficient to study Higgs physics. We then review the CLICHE option [3] before introducing SAPPHiRE and discussing it in more detail. We then review briefly some of the most interesting physics measurements possible with a $\gamma\gamma$ Higgs Factory, which could include accurate measurements of M_h , $\Gamma(h \rightarrow \gamma\gamma) \times \mathcal{BR}(h \rightarrow \bar{b}b)$, $\Gamma(h \rightarrow \gamma\gamma) \times \mathcal{BR}(h \rightarrow WW^*)$, $\Gamma(H \rightarrow \gamma\gamma) \times \mathcal{BR}(H \rightarrow \gamma\gamma)$, and the CP properties of the $h \rightarrow \gamma\gamma$ coupling, following [3]. We conclude by discussing comparisons and possible synergies with other accelerator projects.

2 Concepts for a $\gamma\gamma$ Higgs Factory

2.1 CLICHE

The CLIC design for a high-energy, high-luminosity electron-positron linear collider uses a two-beam acceleration scheme, with conventional normal-conducting structures accelerating the low-energy, high-intensity drive beams. The main beams are accelerated by RF structures whose power is obtained by decelerating the drive beams in parallel beam lines. Two-beam acceleration has been demonstrated successfully in CLIC test facilities (CTF1, CTF2 and CTF3). A possible future step, called CLIC 1, would provide a full-scale test of beam dynamics and power handling using a 70-GeV CLIC module. A pair of such modules could provide a large geometric luminosity for e^-e^- collisions. It was proposed in [3] that suitable laser backscattering systems could provide a large effective luminosity for $\gamma\gamma$ collisions with centre-of-mass energies around the mass of a light Higgs boson, providing a relatively economical $\gamma\gamma$ Higgs factory, the CLIC Higgs Experiment (CLICHE). Fig. 1 displays a sketch of the possible layout of CLICHE, and Table 1 lists some example parameters for CLICHE, as optimized in [3] for a hypothetical Higgs mass $M_h \sim 115$ GeV. These parameters should be adjusted for the current $M_h \sim 125$ GeV: in particular, the beam energy should be increased by ~ 5 GeV, and the electric power required would increase correspondingly. Table 2 lists some example parameters for the mercury laser system and photon beams of CLICHE: these parameters should also be reviewed, in light of technological developments since [3] and the increased centre-of-mass energy. The CLICHE $\gamma\gamma$ luminosity spectra for the spin-0 and spin-2 states are shown in the left panel of Fig. 2, and the effective polarization is shown in the right panel.

2.2 SAPPHiRE

Here we propose an alternative strategy for realizing a $\gamma\gamma$ Higgs factory, inspired by the recent design of the Large Hadron-electron Collider (LHeC) [4] that employs a pair of recirculating linacs capable of increasing the e^- energy by ~ 10 GeV in each pass. A $\gamma\gamma$ Higgs factory would require an e^-e^- centre-of-mass energy of $\sim 125 \text{ GeV}/0.8/2 \sim 80$ GeV. This would be achieved in SAPPHiRE via four passes through two superconducting recirculating linacs, as illustrated in Fig. 3. Compared to the LHeC, one additional arc is required on either side, corresponding to beam energies of 70 and 80 GeV, respectively. The 80 GeV arc is split into two halves with the collision point at the centre.

The last column of Table 1 compiles a list of example parameters for SAPPHiRE, which would meet the luminosity target of $\mathcal{L}_{\gamma\gamma} \sim 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. As in the case of CLICHE, the photon beams are produced by Compton backscattering of laser light off the 80 GeV electron bunches, and the Compton scattering points are taken to be about 1 mm away from the main $\gamma\gamma$ collision point. Laser pulses are required at a rate of 200 kHz. For a photon energy of 3.53 eV, equivalent to a laser wavelength of 351 nm, we have $x = 4.3$ (where $E_{\gamma,\text{max}} = x/(1+x)E \approx 65$ GeV). These laser parameters are similar to those proposed for the CLICHE design, as listed

Table 1: *Example parameters for $\gamma\gamma$ colliders based on CLIC-1 (CLICHE, left column), as optimized for $M_h \sim 115$ GeV [3], and a pair of recirculating superconducting linacs (SAPPHiRE, right column) optimized for $M_h \sim 125$ GeV.*

Variable	Symbol	CLICHE [3]	SAPPHiRE
Total electric power	P	150 MW	100 MW
Beam energy	E	75 GeV	80 GeV
Beam polarization	P_e	0.80	0.80
Bunch population	N	4×10^9	10^{10}
Number of bunches per train	n_b	154	—
Number of trains per rf pulse	n_t	11	—
Repetition rate	f_{rep}	100 Hz	cw
Average bunch frequency	$\langle f_{\text{bunch}} \rangle$	169 kHz	200 kHz
Average beam current	I_{beam}	0.11 mA	0.32 mA
RMS bunch length	σ_z	30 μm	30 μm
Crossing angle	θ_c	≥ 20 mrad	≥ 20 mrad
Normalised horizontal emittance	ϵ_x	1.4 μm	5 μm
Normalised vertical emittance	ϵ_y	0.05 μm	0.5 μm
Nominal horizontal beta function at the IP	β_x^*	2 mm	5 mm
Nominal vertical beta function at the IP	β_y^*	20 μm	0.1 mm
Nominal RMS horizontal IP spot size	σ_x^*	138 nm	400 nm
Nominal RMS vertical IP spot size	σ_y^*	2.6 nm	18 nm
Nominal RMS horizontal CP spot size	$\sigma_x^{C,*}$	154 nm	400 nm
Nominal RMS vertical CP spot size	$\sigma_y^{C,*}$	131 nm	180 nm
e^-e^- geometric luminosity	\mathcal{L}	$4.8 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$	$2.2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

Table 2: *Example parameters for the CLICHE mercury laser system [3], and for the SAPPHiRE laser system, assuming $\mathcal{L}_{ee} = 4.8 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and $\mathcal{L}_{ee} = 2.2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, respectively.*

Variable	Symbol	CLICHE [3]	SAPPHiRE
Laser beam parameters			
Wavelength	λ_L	0.351 μm	0.351 μm
Photon energy	$\hbar\omega_L$	3.53 eV = 5.65×10^{-19} J	3.53 eV
Number of laser pulses per second	N_L	169400 s^{-1}	200000 s^{-1}
Laser peak power	W_L	$2.96 \times 10^{22} \text{ W/m}^2$	$6.3 \times 10^{21} \text{ W/m}^2$
Laser peak photon density		$5.24 \times 10^{40} \text{ photons/m}^2/\text{s}$	$1.1 \times 10^{40} \text{ photons/m}^2/\text{s}$
Photon beam			
Number of photons per electron bunch	N_γ	9.6×10^9	1.2×10^{10}
$\gamma\gamma$ luminosity for $E_{\gamma\gamma} \geq 0.6 E_{CM}$	$\mathcal{L}_{\gamma\gamma}^{\text{peak}}$	$3.6 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$	$3.6 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$

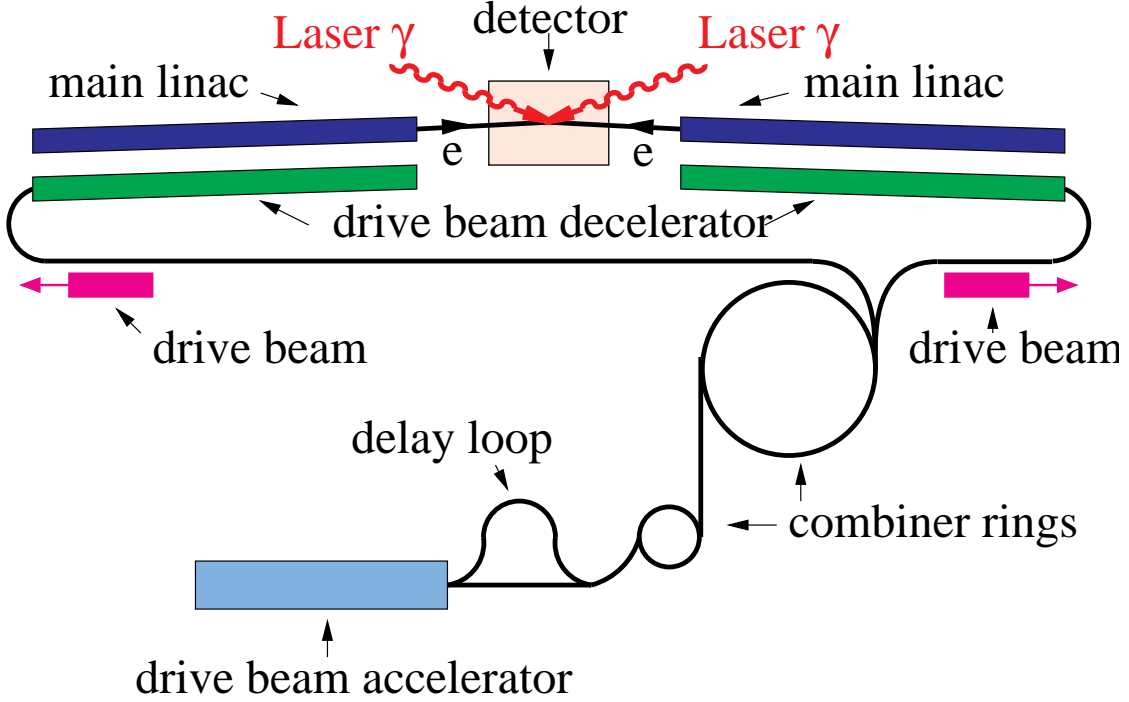


Figure 1: *Sketch of the possible layout of a $\gamma\gamma$ collider based on CLIC 1, the CLICHE concept [3].*

in Table 2 ¹. The laser parameters can be relaxed by pulse stacking in an optical resonant cavity, e.g. with ten recirculations between collisions (implying a total path length of 150 m in the optical cavity) and with a single-pass power reflectivity of $R = 99.99\%$, the power enhancement is a factor of 100. The electron beam cross section at the Compton conversion point is about 4 times larger than for CLICHE. For efficient conversion, the total energy of a laser pulse should be a few Joule, e.g., 1 TW peak power and 5 ps pulse length, implying 1 MW average power.

The SAPPHiRE $\gamma\gamma$ luminosity spectra are shown in the plots of Fig. 4. In the left panel various normalized distances $\rho \equiv l_{\text{CP-IP}}/(\gamma\sigma_y^*)$, (where $l_{\text{CP-IP}}$ is the distance between the IP and the Compton backscattering point, γ is the electron boost factor and σ_y^* is the vertical electron beam width at the IP) are compared, with $\rho = 0.4$ corresponding to the SAPPHiRE parameters listed in Table 1. The right plot shows the effect of different beam and laser polarization configurations (with P_e the polarization of the electrons and λ the polarization of the laser photons). The SAPPHiRE electron beams polarization is assumed to be 80%.

The energy loss per arc is given by

$$E_{\text{arc}}[\text{GeV}] = 8.846 \times 10^{-5} \frac{(E [\text{GeV}])^4}{2\rho [\text{m}]} . \quad (1)$$

¹As an alternative to the mercury laser technology considered in [3], nowadays it is conceivable also that fibre lasers could provide the performance required (see e.g. [5]).

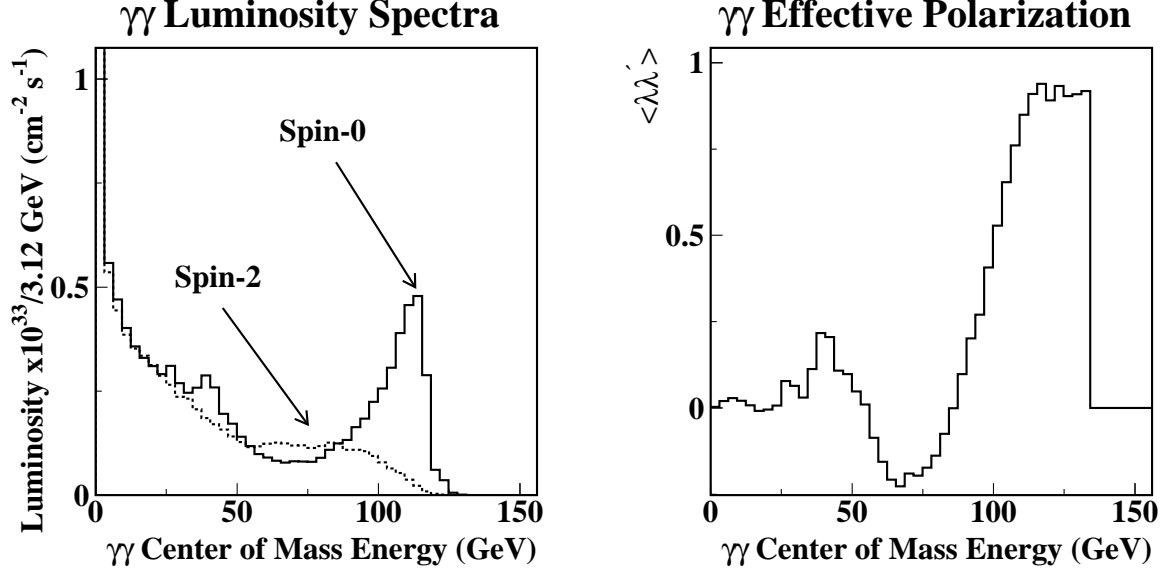


Figure 2: *Luminosity spectra and beam polarization as functions of $E_{CM}(\gamma\gamma)$ for the CLICHE parameters [3] for 75 GeV electrons obtained with DIMAD [6] and CAIN [7] for $\mathcal{L}_{ee} = 4.8 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.*

For a bending radius of $\rho = 764$ m, as in the LHeC design, the energy loss in the various arcs is summarized in Table 3. We see that each beam loses about 5 GeV in energy, which can be compensated by increasing the voltages of the two linacs from 10 GV to 10.63 GV. The largest energy loss due to synchrotron radiation for beams in a common arc occurs at 70 GeV, and amounts to 1.39 GeV, or 2%. With a dispersion of 0.1 m (see [8]), the orbit change would be 2 mm. The two beams would certainly fit into a common beam pipe.

The additional energy spread from synchrotron radiation is given by

$$\Delta\sigma_E^2 = \frac{55\alpha(\hbar c)^2}{48\sqrt{3}} \gamma^7 \frac{\pi}{\rho^2}, \quad (2)$$

where $R \approx 1$ km is the geometric radius, and ρ is the dipole bending radius in the arc. The total rms energy spread induced by synchrotron radiation is only 0.071%, as also listed Table 3.

The emittance growth due to synchrotron radiation is given by

$$\Delta\epsilon_{/N} = \frac{2\pi}{3} \frac{c_q r_e}{\rho^2} \gamma^6 \langle H \rangle, \quad (3)$$

where $C_q = 3.8319 \times 10^{-13}$ m, and ρ is the bending radius. For the LHeC design with $l_{\text{bend}} \approx 40$ m the total length of the bending magnets per optical (TME) cell, and $\rho = 764$ m, we find $\langle H \rangle = 1.2 \times 10^{-3}$ m [8], which is close to the “useful and realistic” minimum emittance optics given in [10]. At 60 GeV the emittance growth of the LHeC optics design is 13 microns,

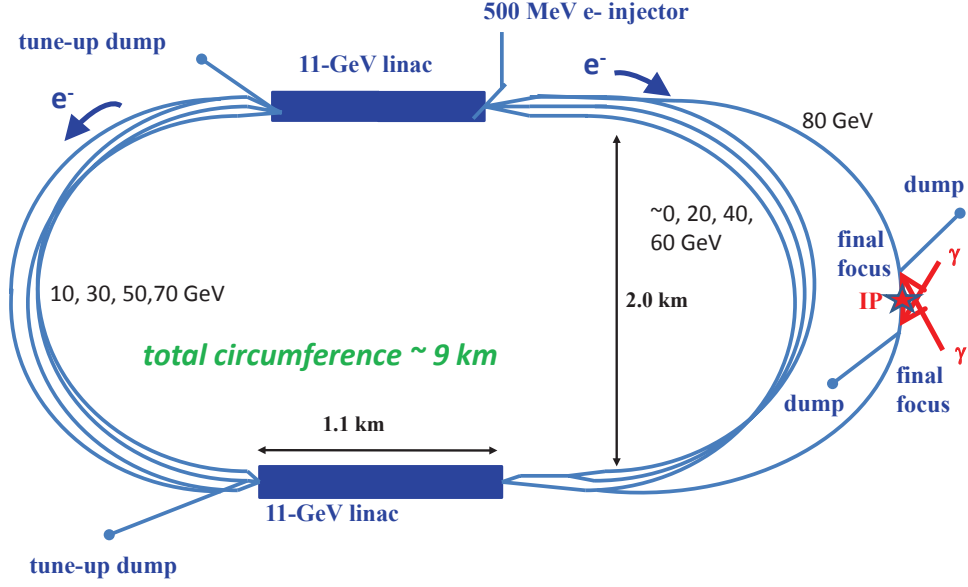


Figure 3: *Sketch of a layout for a $\gamma\gamma$ collider based on recirculating superconducting linacs – the SAPPHiRE concept.*

Table 3: *Energy losses and energy spread induced in the 8 arcs of SAPPHiRE.*

beam energy [GeV]	ΔE_{arc} [GeV]	$\Delta\sigma_E$ [MeV]
10	0.0006	0.038
20	0.009	0.43
30	0.05	1.7
40	0.15	5.0
50	0.36	10
60	0.75	20
70	1.39	35
80 (1/2 arc)	1.19	27
total	3.89	57

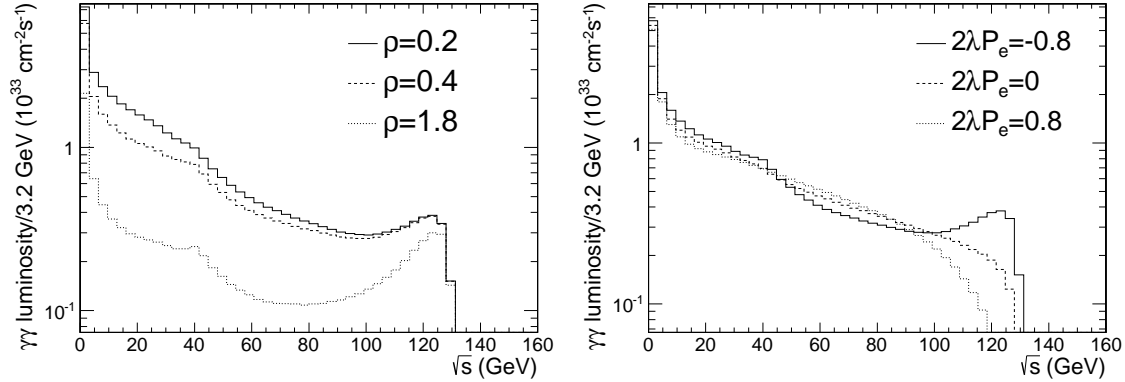


Figure 4: *Luminosity spectra for SAPPHiRE as functions of $E_{CM}(\gamma\gamma)$, computed using Guinea-Pig [9] for three possible normalized distances (left) and different polarizations of incoming particles (right).*

too high for our purpose, and the extrapolation to 80 GeV with the sixth power of the energy is unfavourable. However, [10] also gives the scaling law $\langle H \rangle \propto l_{\text{bend}}^3 / \rho^2$. This suggests that by reducing the cell length and associated dipole length by a factor of 4 (to a total length of $l_{\text{bend}} = 10$ m per cell) we can reduce the horizontal normalized emittance growth at 80 GeV to 1 micron, which would be adequate for SAPPHiRE.

Beams with an emittance ratio of 10 can be produced with a flat-beam electron gun using the transformer concept described in [11]. Starting with a normalized uncorrelated emittance of $4\text{--}5\ \mu\text{m}$ and a bunch charge of $0.5\ \text{nC}$, the injector test facility at the Fermilab A0 line achieved emittances of $40\ \mu\text{m}$ horizontally and $0.4\ \mu\text{m}$ vertically, with an emittance ratio of 100 [12]. For the $\gamma\gamma$ collider we need a similar emittance ratio of 10, but a bunch charge three times larger ($1.6\ \text{nC}$) and a smaller initial emittance of $1.5\ \mu\text{m}$. These parameters are within the present state of the art (e.g., the LCLS photoinjector routinely achieves $1.2\ \mu\text{m}$ emittance with a $1\ \text{nC}$ bunch charge).

We conclude that there are no obvious showstoppers for the SAPPHiRE concept, which employs plausible accelerator parameters.

3 Physics with a $\gamma\gamma$ Higgs Factory

We base our short discussion here on the exploratory studies of the CLICHE $\gamma\gamma$ collider, incorporating modifications associated with the measured Higgs mass $M_h \sim 125\ \text{GeV}$ compared to the hypothetical value of $115\ \text{GeV}$ assumed in [3]. As discussed in some detail there, several important measurements of Higgs properties can be made at a Higgs factory and running around the Higgs threshold offers important advantages for several analyses. Ref. [3] also

discusses other physics opportunities that we do not dwell upon here.

Higgs Production

The excitation curves for Higgs boson production are shown in Fig. 5 assuming 80% longitudinal polarization for the electron beams and circularly polarized lasers. As seen in the left panel, the Higgs production cross section rises rapidly for $154 \text{ GeV} < E_{CM}(e^-e^-) < 164 \text{ GeV}$, providing a physics opportunity for a $\gamma\gamma$ collider obtained by laser backscattering from a pair of e^- beams with energies $\sim 80 \text{ GeV}$. The right panel of Fig. 5 shows the cross section as a function of Higgs mass in the range $120 \text{ GeV} < M_h < 140 \text{ GeV}$ for three choices of $E_{CM}(e^-e^-)$. The excitation curve is decreased by a factor ~ 3 if the electron beams are unpolarized. The nominal luminosity of CLICHE or SAPPHiRE would yield $\sim 20,000$ Higgs bosons per year: increasing the SAPPHiRE beam power by a factor ~ 2 would increase the luminosity and hence the number of Higgs bosons produced by ~ 4 .

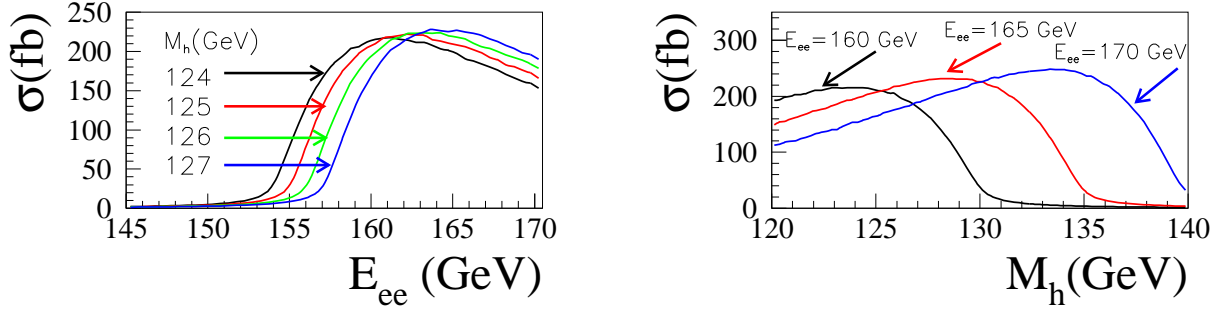


Figure 5: (a) The cross sections for $\gamma\gamma \rightarrow h$ for different values of M_h as functions of $E_{CM}(e^-e^-)$. (b) The cross section for $\gamma\gamma \rightarrow h$ as a function of M_h for three different values of $E_{CM}(e^-e^-)$. We assume that the electrons have 80% longitudinal polarization and that the lasers are circularly polarized, so that the produced photons are highly circularly polarized at their maximum energy.

Mass Measurement

The sharp edge of the $\gamma\gamma$ luminosity function seen in Fig. 2 and 4 provides an opportunity to measure M_h accurately by varying the electron beam energy. As it crosses the Higgs production threshold, the number of Higgs events increases dramatically, as reflected in the sharp excitation curves in Fig. 5. The position of this rise enables one to measure the Higgs mass, as discussed in [13] and in the context of CLICHE in [3], where it was shown that the point of maximum sensitivity to the Higgs mass is a few GeV below the peak of the cross section. It was found that a run of one year at the peak and half a year each on and below threshold would enable M_h to be measured with an accuracy $\sim 100 \text{ MeV}$, see Fig. 6.

$h \rightarrow \bar{b}b$ Decay

The large branching ratio for $h \rightarrow \bar{b}b$ decay for $M_h \sim 125 \text{ GeV}$ makes it the main channel

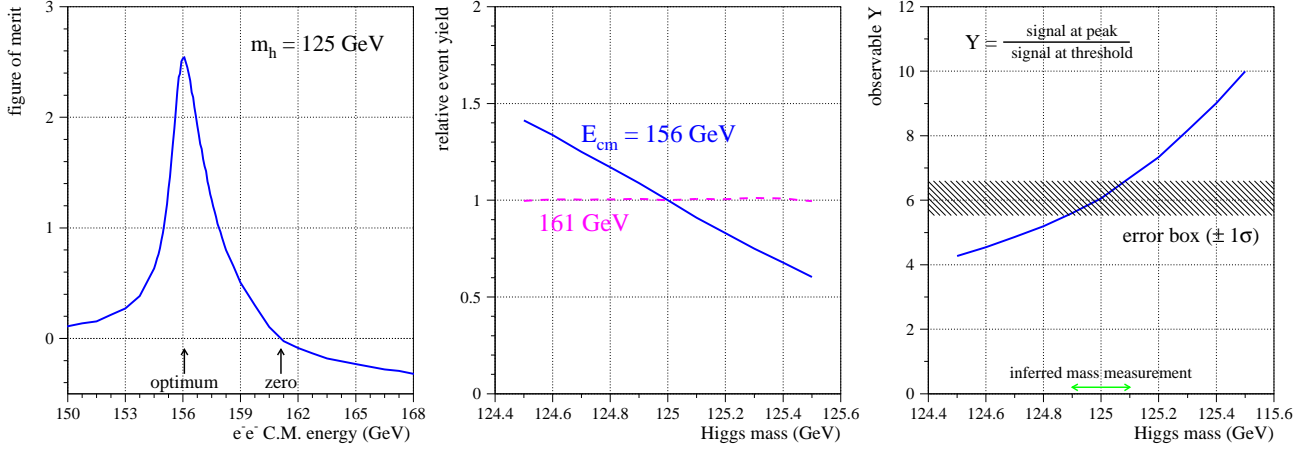


Figure 6: (a) A figure of merit quantifying the measurement error on M_h as a function of the $E_{CM}(e^-e^-)$. The energies with maximum and zero sensitivity are marked. (b) The relative yields of a 125 GeV Higgs boson at the points of maximum and zero sensitivity to M_h . (c) Behavior of the observable $Y \equiv \text{signal at peak} / \text{signal at threshold}$ as a function of m_H , and the projected error.

for Higgs studies at a $\gamma\gamma$ collider, so this channel has received considerable attention. We analyzed this in the context of the CLICHE study [3], including perturbative QCD backgrounds, assuming cuts with an efficiency of 85 to 90% for the 33% of $\bar{b}b$ events that do not contain neutrinos, 70% efficiency for double-tagging of $\bar{b}b$ final states and a 3.5% $\bar{c}c$ contamination. Results from the CLICHE study for $M_h = 115$ GeV are shown in Ref. [3], and we expect similar results for $M_h \sim 125$ GeV. The corresponding accuracy in measuring $h \rightarrow \bar{b}b$ decay is 2%, as reported in Table 4.

$h \rightarrow WW^*$ Decay

This decay was also studied in [3] for $M_h = 115$ GeV. In the case, the situation for $M_h \sim 125$ GeV is somewhat different, since on the one hand the expected $h \rightarrow WW^*$ branching ratio is higher than for $M_h = 115$ GeV, but on the other hand the cross section for the background process $\gamma\gamma \rightarrow WW^*$ increases rapidly with the centre-of-mass energy [14], see Fig. 7. In the absence of a more detailed study, however, we expect that a precision similar to that found in [3] could be achieved, namely $\sim 5\%$ as also reported in Table 4.

$h \rightarrow \gamma\gamma$ Decay

The decay $h \rightarrow \gamma\gamma$ is rare one, but the large number of Higgs events a $\gamma\gamma$ collider would include an interesting number of $h \rightarrow \gamma\gamma$ events. Moreover, the backgrounds are expected to be small, and initial estimates in [3] indicated that a peak should be observable in the $\gamma\gamma$ mass distribution. The quadratic dependence of the number of events $\sim \Gamma_{\gamma\gamma}^2 / \Gamma_{total}$ implies that if Γ_{total} could be measured accurately elsewhere, a $\gamma\gamma$ collider would yield a small error in $\Gamma_{\gamma\gamma}$. Conversely, if $\Gamma_{\gamma\gamma}$ were to be measured elsewhere, a small error Γ_{total} could be obtained. In Table 4 we see that a 10% measurement or better of $\sim \Gamma_{\gamma\gamma}^2 / \Gamma_{total}$ could be made within a year

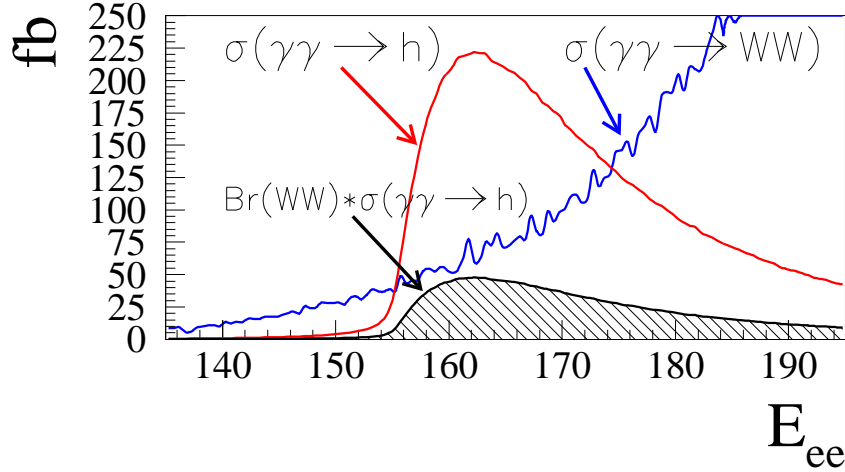


Figure 7: Cross sections for $\gamma\gamma \rightarrow h$, $\gamma\gamma \rightarrow h \times \mathcal{BR}(h \rightarrow WW)$ for $m_H = 125$ GeV and $\gamma\gamma \rightarrow WW$ production, as calculated using Pandora [14].

of data-taking.

Other Decay Modes

We expect that $h \rightarrow ZZ^*$ and $h \rightarrow Z\gamma$ should be observable at a $\gamma\gamma$ collider, but have not made any studies. Pessimism was expressed in [3] about the prospects for observing $h \rightarrow \tau^+\tau^-$, but we think this should be revisited. Likewise, Ref. [3] was pessimistic about measuring $h \rightarrow \bar{c}c$ and gg , in these case probably correctly.

Summary of Possible Measurements

We have summarized the possibilities for measurements in the $h \rightarrow \bar{b}b, WW^*$ and $\gamma\gamma$ channels. The observabilities and plausible statistical errors in measuring the products $\sigma(\gamma\gamma \rightarrow h)\mathcal{BR}(h \rightarrow X)$ for these channels are reported in Table 4. Studies conducted in the context of CLICHE indicated that the systematic errors could be controlled to similar levels. In addition, M_h could be measured in four ways (fitting the peaks in the $\bar{b}b$, $\gamma\gamma$ and ZZ^* mass distributions, and by the threshold method). Moreover, possible CP asymmetries could be measured with a precision of about 5%.

4 Final Comments

A $\gamma\gamma$ collider could produce a number of Higgs bosons comparable to an e^+e^- Higgs factory. The backgrounds from conventional $\gamma\gamma$ collisions would be larger than the e^+e^- -induced back-

Table 4: *The statistical errors on selected decay modes of a 125 GeV Higgs boson in the Standard Model, calculated for a sample of 20,000 Higgs bosons corresponding to one year with the nominal luminosity of CLICHE or SAPPHiRE.*

decay mode	raw events/year	S/B	ϵ_{sel}	\mathcal{BR}	$\Delta\Gamma_{\gamma\gamma}\mathcal{BR}/\Gamma_{\gamma\gamma}\mathcal{BR}$
bb	11540	4.5	0.30	57.7%	2%
W^+W^-	4300	1.3	0.29	21.5%	5%
$\gamma\gamma$	45	—	0.70	0.23%	8%

grounds to the reaction $e^+e^- \rightarrow Zh$, and an e^+e^- collider would have other possibilities at other energies, e.g., for Z studies at lower energies, or for $t\bar{t}$ studies at higher energies. Nevertheless, we feel that the Higgs physics programme of a $\gamma\gamma$ collider is of comparable interest to that with an e^+e^- collider, bearing in mind, e.g., the possibilities for CP studies that we have not discussed here.

In this note we have presented two concepts for a $\gamma\gamma$ collider: the CLICHE idea based on CLIC 1 [3], and the SAPPHiRE idea based on the recirculating linacs envisaged for the LHeC [4]. These concepts therefore offer considerable synergies with these other projects. Moreover, we note two generic advantages of $\gamma\gamma$ colliders over e^+e^- colliders: they need a lower centre-of-mass energy and they do not need a positron source. Both of these features offer potential economies, though they may be offset by other disadvantages, such as the need for a high-performance laser backscattering system. This is presumably the aspect of a $\gamma\gamma$ collider that requires the most R&D, though one should be able to piggy-back on the developments in laser systems made for other purposes.

Finally, we note that, although the SAPPHiRE concept was motivated by the recirculating linac system proposed for the LHeC, it is not limited to the context of that project. One could well imagine building such a recirculating linac system independently, and it might provide an appealing, timely and cost-efficient stand-alone possibility for a Higgs factory.

Acknowledgements

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